Enhancing Human-Machine System Performance by Introducing Artificial Cognition in Vehicle Guidance Work Systems

Prof. Dr.-Ing. Axel Schulte
Universität der Bundeswehr München
Institute of Flight Systems (LRT-13)
85577 Neubiberg, GERMANY

axel.schulte@unibw.de

ABSTRACT

This paper advocates the introduction of so-called cognitive and cooperative automation into vehicle guidance work systems. The work system of UAV guidance will be taken as an example. This idea radically breaks with the traditional approach of supervisory control. According to our approach the human will no longer be the only instance in the work process being responsible for the pursuit of the given work objective. We call this novel mode of human-automation interaction cooperative control. Suchlike automation will take over a more active part and develop its own initiative to achieve the aim of work and thereby enhance the human-machine system's performance. This paper provides a comprehensive description of the top-level work system design incorporating cognitive automation, a brief outline on the realisation of artificial cognition and the description of an application example taken from the multi-UAV guidance and mission management domain. The experiments show that cognitive cooperation provides a high potential for human performance enhancement on the level of cognitive work.

1.0 INTRODUCTION

Vehicle guidance of any kind has always been a very demanding task for human operators. Driving a car and navigating in dense traffic is probably the most complex sensori-motor and cognitive task an average person is ever exposed to in daily life. In fact, a whole set of psycho-physiological limitations confine human performance, e.g. associated with visual perception or reaction time. Fatigue might as well be a major issue. Obviously operating a military aircraft requires much more specialised human capabilities and poses extremely high demands on pilots. In addition to the aforementioned problems physiological human performance limitations in connection with e.g. acceleration tolerance, hypoxia or motion sickness arise. With the advent of more and more automation in the work environment the nature of work has been changed considerably. Many of the purely manual control tasks vanished, while *supervisory control* [1] became the predominant mode of human-machine interaction in vehicle guidance. This led to a great relief from demanding high-bandwidth tasks and the size of operating crews could be considerably scaled down, e.g. the flight deck crew of civil airliners from four or even five persons in the earlier years to two pilots as usual today. Accompanied with that, however, work environments became much more complex, requiring increasing skills and knowledge on behalf of the human operators in order to still cope with the complexity. In fact, human cognitive performance limits became the predominant restriction. Unless high efforts invested in the optimisation of human-machine systems typical reactive designs could not really succeed in counteracting suchlike problems. Cognitive and cooperative automation represent novel approaches to this problem, radically breaking with the tradition of supervisory controlled automation. The Institute of Flight Systems (and it's predecessor organisations) at the Universität der Bundeswehr München (Munich University of the German Armed Forces) has been working on experimental prototypes since more than two decades now. Many experimental works proving the concepts have been performed enhancing human-system performance in particular in aerial applications.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
OCT 2009	**N/A**	**-**

4. TITLE AND SUBTITLE
Enhancing Human-Machine System Performance by Introducing Artificial Cognition in Vehicle Guidance Work Systems

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Universität der Bundeswehr München Institute of Flight Systems (LRT-13) 85577 Neubiberg, GERMANY

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA562561. RTO-MP-HFM-181 Human Performance Enhancement for NATO Military Operations (Science, Technology and Ethics) (Amelioration des performances humaines dans les operations militaires de l'OTAN (Science, Technologie et Ethique)). RTO Human Factors and Medicine Panel (HFM) Symposium held in Sofia, Bulgaria, on 5-7 October 2009., The original document contains color images.

14. ABSTRACT
This paper advocates the introduction of so-called cognitive and cooperative automation into vehicle guidance work systems. The work system of UAV guidance will be taken as an example. This idea radically breaks with the traditional approach of supervisory control. According to our approach the human will no longer be the only instance in the work process being responsible for the pursuit of the given work objective. We call this novel mode of human-automation interaction cooperative control. Suchlike automation will take over a more active part and develop its own initiative to achieve the aim of work and thereby enhance the human-machine systems performance. This paper provides a comprehensive description of the top-level work system design incorporating cognitive automation, a brief outline on the realisation of artificial cognition and the description of an application example taken from the multi-UAV guidance and mission management domain. The experiments show that cognitive cooperation provides a high potential for human performance enhancement on the level of cognitive work.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**22**	

In order to provide a closer insight into the approach of cognitive and cooperative automation in the following chapters the work system will be introduced as human factors engineering theory and applied to the field of multi-UAV guidance. The work system allows a systematic systems engineering approach of deriving requirements for so-called Artificial Cognitive Units (ACUs). In the next chapter a brief description will be given, how an ACU shall be built, in order to be enabled to yield knowledge-based behaviour. Finally, in the following chapter an example application of multi-UAV guidance and mission management will be described and respective experimental results will be given.

2.0 WORK PROCESS ANALYSIS OF HUMAN-MACHINE SYSTEMS

2.1 Work Process and Work System

To figure out a solution to the challenges of future vehicle guidance systems, the first step shall be the characterisation of today available conventional automation in the work process as opposed to the introduction of cognitive automation. Therefore, the consideration of the *work system* as top-level human factors engineering framework shall be used. The work system (see Figure 1) as a general ergonomics concept has been utilised in a modified definition, adapted to the application domain of human-machine cooperation in flight guidance by [2] and to machine-machine cooperation by [3].

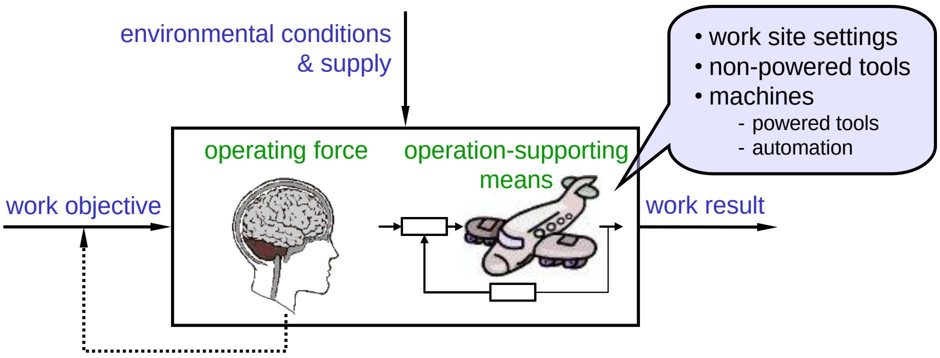

Figure 1: Work system

The work system is defined by the work objective, being the main input into the process of work. The work objective mostly comes as an instruction, order or command from a different supervising agency with its own work processes. Further constraining factors to the work process are environmental conditions and supplies. At its output, the work system provides the work result including the current state of work and what has been accomplished by the work process as a physical change of the real world [4].

The work system itself consists of two major elements, i.e. the operating force and the operation-supporting means, as characterised in some more detail in the following:

- The *operating force* is the high end decision component of the work system. It is the only component which pursues the complete work objective. It determines and supervises what will happen in the course of the work process and which operation-supporting means will be deployed at what time. The operating force is the work system component with the highest authority level. One major characteristic of especially a human representing the operating force is the capability of defining the work objective by himself (see Figure 1). Besides operating on the basis of full authority competence this is the decisive criterion for what we call an *autonomous system* (see also discussion below).

- The concept of *operation-supporting means* can be seen as a container for whatever artefacts are available today to make use of in the work process, including basic work site settings, non-powered tools and machines. The latter might be a vehicle in the case of a transport work process, but also computerised devices of automation. A robotic system in this sense could be seen as highly automated machine as part of the operation-supporting means of a work system as well. In the application domain of flight guidance currently used auto-flight or autopilot systems including the human-machine control interface can serve as typical examples for automation. Common to the nature of various operation-supporting means is the fact that they facilitate the performance of certain sub-tasks, and only that. By nature, such a sub-task does not form a work system by itself, obviously being only one part of another higher level work task. According to the common ergonomic design philosophy, mostly the operation-supporting means are subjected to the endeavours of optimisation in order to achieve overall system requirements and accomplish further improvements.

As mentioned earlier, these elements will be combined within the work system in order to achieve a certain work result on the basis of a given work objective. The accomplishment of a flight mission (i.e. the work objective) may give a good idea of what is meant here. In this case, the work system will consist of an air-crew being the operating force, and the aircraft including its automated on-board functions as well as any required infrastructure representing the operation-supporting means.

The replacement of human work by continuously expanding automated functions, as it could be observed throughout the whole history of industrial mechanisation and automation, leads to technical solutions of steadily increased authority. Simultaneously, the human operator is continuously being pushed further into the role of supervising more and more machines and, at the same time, more and more complex ones. The process of substituting the responsibilities of the human in a work system might be driven up to a degree where the operator’s capabilities would be completely substituted by automated functions. From a purely technology minded standpoint, the human could theoretically be dropped out of the work system as a consequence. In case that the automation is just like the human capable and allowed to self-assign a work objective, the resulting artefact could be called an *artificial autonomous system* (see Figure 2).

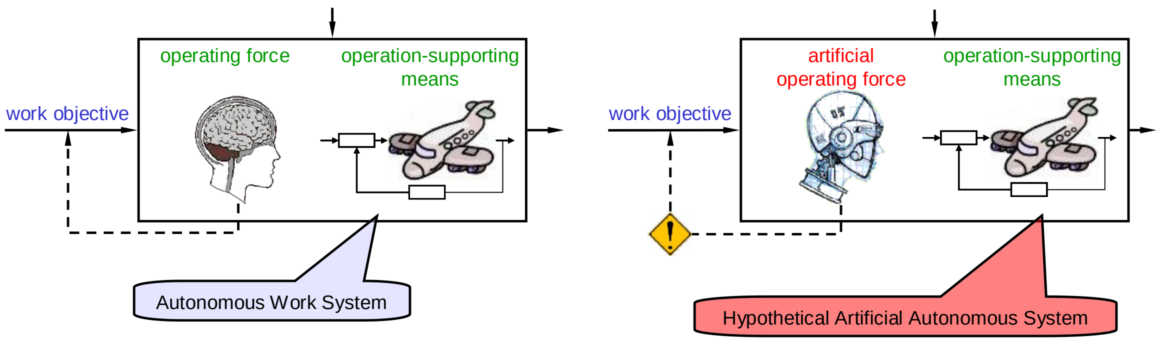

Figure 2: Hypothetical conversion of an ordinary autonomous work system with human operator into an artificial autonomous system

However, considering such an artificial autonomous system, there are two good reasons, why it is not desirable to create a machine like this:

- From an *ethical* point of view we want to refuse building machines, which potentially could self-assign a work objective, as long as this implies the possibility of unforeseeable, harmful consequences for us humans.

- From a *pragmatic* point of view we do not need machines not being subjected to human authority. Such technological artefacts for themselves are of no use, since they are no longer serving the human for his work in its broadest sense.

Still, technology may provide very powerful automation capabilities replacing human performance if useful, unless it is not entitled to the authority of self-assigning a work objective. We call the resulting artefact a(n) (artificial) semi-autonomous system, the structure of which is very similar to that of a work system. Figure 3 shows such a semi-autonomous system which is always part of the operation-supporting means of a superior work system. In this set-up, this operation-supporting semi-autonomous system will not be allowed to self-define an objective. It will receive it from the operating force of the associated work system which at least comprises one human operator. Surely, such a semi-autonomous system may work very independently, without continuous guidance by the operating force.

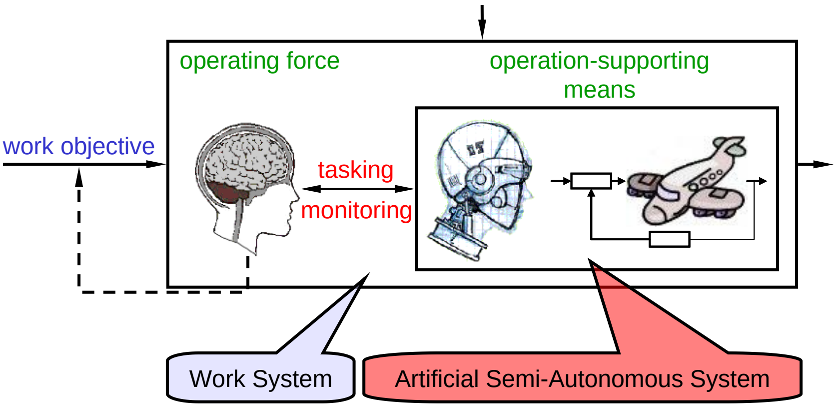

Figure 3: Semi-autonomous system as part of a work system

In conclusion, the definition of a work system excludes the existence of a purely artificial one. There will be no artificial autonomous system addressed as a work system. There will be no artificial system addressed which would have got the capacity to generate a work objective on its own. Instead, we claim the necessary condition that there will be at least one human operator as part of the operating force of the work system. In other words, every technological artefact, no matter how high its "level of autonomy" might be advertised by its creators, will finally either support human work (as part of a work system) in its broadest sense or not be of any use at all.

2.2 Experiences with complex automation

The concept of having conventionally automated functions in the work process as low authority artificial specialists being good for a particular execution support but lacking the full perspective, was very convenient as long as only simple automated functions were used for simple tasks. It was of no harm that the responsibility load not to violate the prime goals of the work process was exclusively on the human operator's shoulders. However, in highly automated work systems for complex and demanding work objectives as we are used to now, like, for instance, a demanding mission of a modern fighter aircraft, the situation is different. Here, conventionally automated functions with a high degree of complexity are accommodated as operation-supporting functions. They are considered as necessary to keep the human operator freed from a sufficiently high number of tasks which otherwise could lead to overloads. This might become critical, though, since with increasing conventional automation complexity, the task of the operator as supervisor becomes more and more complex, too. Instead of the intended unloading, danger of overcharge of the operator may inevitably arise in certain situations, resulting in a loss of situation awareness and control performance, i.e. lacking to comply with the prime goals. The operator might be

unaware of discrepancies between sub-task activities of automated functions or/and the prime goal necessities or even of his insufficiency to adapt to this inadequacy. This is just the opposite of what was intended by the introduction of automation. [4]

This issue fits well the characteristics of a vicious circle. With respect to the extension of conventional automation, such a vicious circle is depicted in Figure 4 for the application field of UAV guidance and control.

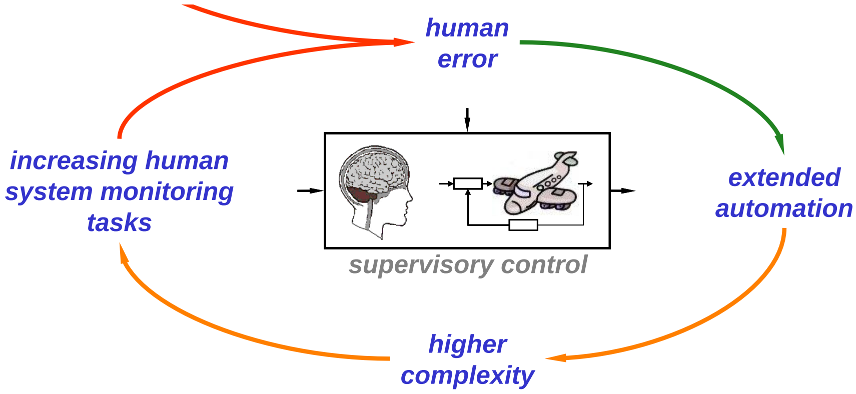

Figure 4: The vicious circle of extending conventional automation

As characteristic of reactive designs to inescapably occurring human error in human supervised automation systems, the extension of automation is taken as solution. Designers transfer the authority over more and more comprehensive work process tasks from the operating force i.e. the human operator to increasingly complex automated functions being part of the operation-supporting means. Although, being relieved from workload in the first place, the human operator will be burdened with extra demands from increasing system monitoring and management tasks. At a certain point the human operator cannot but fail in the supervision of suchlike automated systems. In reaction, as being used to, typically the only solution considered is to further extend the share of automation as part of the operation-supporting means in conjunction with further increase of complexity. In conclusion, as we are interested in a design with gains in productivity of a work system, we experience that the increase of system complexity due to further addition of conventional automation results in less and less increase of productivity gain and might eventually even end up with decreases.

The deficiencies of conventional automation finally leading to the vicious circle described have been experienced for quite a time now (see [5]) and are well-captured in explicit terms in the meantime by the phenomena known under e.g. automation brittleness, opacity (entailing increased demands on monitoring the automation status), literalism, clumsiness, and data overload, all of them being consequences of too high system complexity.

2.3 Dual-Mode Cognitive Automation

Traditionally, a human or a human team (cf. e.g. [2]) represents the operating force in the work system. In the conventional sense the human operating force provides the capability of cognition within a work system, whereas the operation-supporting means do not. In order to overcome known shortcomings of such conventional automation (e.g. [5][6]) which is oftentimes by far too complex to be handled properly, a configuration of the work system is suggested, where so-called *Artificial Cognitive Units* (ACU) are introduced.

Inserting ACUs into the work system as opposed to the further enhancement of conventionally automated functions or the addition of further humans (first row in Figure 5) adds a new level of automation, i.e. the *cognitive level* to the work system (second row in Figure 5). The possibility to shape an ACU being either part of the operating force (*operating ACU*) or being part of the operation-supporting means (*supporting ACU*) defines *two modes of cognitive automation* [4]. Both modes might be combined together with conventional automation within one work system.

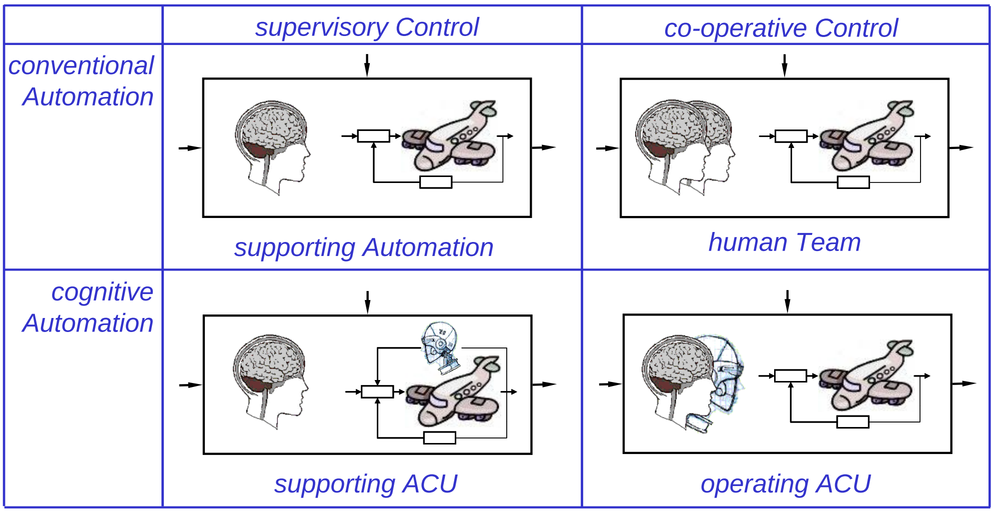

Figure 5: Introducing Artificial Cognitive Units (ACUs) into the work system

Common to these two modes of automation is that they incorporate artificial cognition. Onken [2] describes the nature of suchlike cognitive automation as follows:

"As opposed to conventional automation, cognitive automation works on the basis of comprehensive knowledge about the work process objectives and goals […], pertinent task options and necessary data describing the current situation in the work process. Therefore, cognitive automation is prime-goal-oriented." [2]

Particularly due to the orientation of its behaviour towards explicitly represented goals and its understanding of the current situation, cognitive automation has the potential to avoid problems of conventional approaches such as complexity and brittleness which have been thoroughly investigated by Billings [5] and others. A detailed explanation of this effect can be found in [4].

Concerning the application of cognitive automation as operating ACU, i.e. on the right hand side of Figure 5, where the human operator and the ACU form the operating force as a team [2] comments that in this configuration the ACU has reached *"[…] the high-end authority level for decisions in the work system, which was, so far, occupied by the human operator alone."* [2]

As a consequence of this consideration both team members – human operator and ACU – have to have the obligation to apply their specific capabilities, which might be overlapping, in order to pursue the overall work objective best. Hence, an operating ACU is always characterised by the incorporation of the functionality of what we call an *assistant system*. Such an assistant system can be a *supplement* to the operating force, i.e. to the human operator or the human team. In this case it is mostly of virtual nature providing informational assistance. On the other hand it can be embodied in an independent machine (e.g. robot, UAV) *substituting* an otherwise necessary additional human operator. In this case the assistance is of physical nature in addition. The design of the corresponding operating force of a work system,

especially the design of the assistant system (i.e. an operating ACU) can be specified by founding it on the compliance with the following basic requirements (see also [7] and [4]):

Requirement 1:

The assistant system has to be able to present the full picture of the work situation from its own perspective and has to do its best by own initiatives to ensure that the attention of the assisted human operator(s) is placed with priority on the objectively most urgent task or subtask.

Requirement 1 leads to functions that become active only at certain, normally rare occasions for contacting the human operator(s) with advisory messages when overtaxing of the human operator(s) seems possible in the task category of situation assessment and interpretation. This takes place in a way such that the human operator(s) can make up his (her/their) mind to accept the advice or not. This function is entirely advisory.

Requirement 2:

If according to requirement 1 the assistant system can securely identify as part of the situation interpretation that the human operator(s) cannot carry out the objectively most urgent task because of overtaxing, then the assistant system has to do its best by own initiatives to automatically transfer this situation into another one which can be handled normally by the assisted human operator(s).

Since requirement 2 is based on sufficient fulfilment of requirement 1, the technical realisation of the assisting function according to requirement 2 consists of two elements (1) to realise reliable identification of situations with overtaxing of the human operator, albeit he or she has got full situation awareness, and (2) to realise reliable automated functionality to overcome this situation. At this point, the assistant system is temporarily replacing a human team member. In essence, the corresponding functions are directly impinging on the work product by automatically carrying out the due tasks which otherwise the human operator was supposed to do. Depending on the situation, explaining information might be given to the human operator that he is enabled to take over again as soon as possible. In the context of describing the essence of temporarily substituting assistance, this problem is being tackled by the work on adaptive automation (see e.g. [8] and [9] for own works in the field)

Requirement 3:

If there are cognitive tasks, the human operator(s) is(are) principally not capable to accomplish, or which are of too high a risk or likely a cause of too high costs, these tasks are to be allocated to the assistant system or operation-supporting means, possibly a supporting cognitive unit.

Requirement 3 refers to an a-priori design decision to transfer certain cognitive tasks within a given work context to the assistant system permanently. This may include that the assistant system decides to utilise certain operation-supporting means in order to fulfil the task. In this case the assistant system can have its own exclusive operation-supporting means at its disposal. Whereas assistant functions derived from requirement 1 or 2 most typically will be carried out at the operator’s work station, assistant functions derived from requirement 3 might as well be dislocated, e.g. aboard a UAV. In this case the operating ACU is guiding the UAV at a high degree of autonomy forming the operating force with the human located somewhere else.

The introduction of an operating ACU is the basis for human-machine symbiosis in its real sense and guides the way out of the vicious circle (see Figure 4) as shown in Figure 6. Although cognitive automation does not break the general trend of raising complexity as such, the introduction of the cooperative control mode counteracts typical problems with supervisory control of increasingly complex

automation by definitely mitigating the system monitoring and management task load through human-automation cooperation.

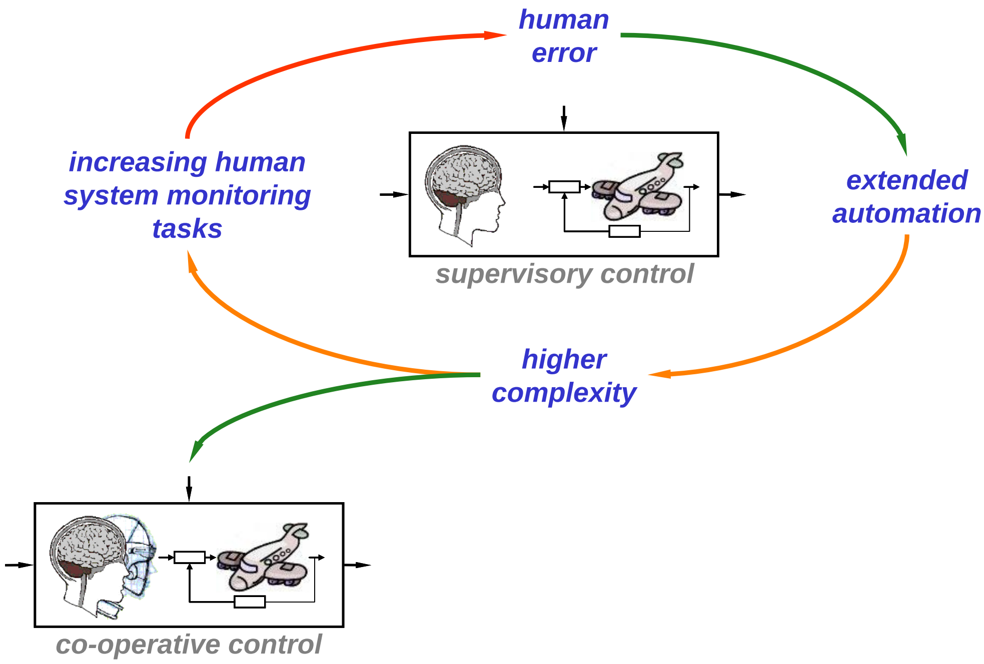

Figure 6: Escaping the vicious circle of progressing automation

2.4 Introduction of Cognitive Automation in UAV Guidance Work System

After having discussed the introduction of cognitive and cooperative automation into work systems in general this section will pick up the UAV guidance work system as an example and discuss several variations of it with respect to the possibilities of introduction of cognitive automation.

To begin with, let us consider a work system for the guidance of multiple UAVs by a single operator without cognitive automation. The UAVs can be used according to their capabilities in order to achieve the work objective. Concerning the tasks of the UAV operator (just considering UAV flight guidance), he usually has to plan and supervise mission plans in parallel processes for several UAVs. Moreover, he has to decide, how his work objective (e.g. area reconnaissance) can be split into several sub-tasks, which UAV shall complete which sub-tasks (e.g. certain sector of area of interest) and how this sub-task can be executed (e.g. definition of a search pattern). The execution of the task is followed by the fusion of the results, as the operator is the only instance within the work system, which has overview of relevant sub-tasks and their dependencies.

In order to support the operator within this work system, additional, cognitive automation can be introduced in different ways. In a first step, the UAVs can be promoted to become semi-autonomous systems, which are operated by a supporting ACU (see Figure 7). This supporting ACU can access necessary information and can control the UAV by the use of various sub-systems or communicate with the operator by data link.

This configuration does not require detailed instructions for the UAVs with respect to how a certain task shall be executed (e.g. specification of a mission plan), but the supporting ACUs are capable of understanding tasks on the abstraction level of a mission order and executing them by the use of available

operation-supporting means. Thus, the UAVs get more independent from highly frequent and detailed instructions from the operator so that there are less critical requirements concerning data link availability and time critical reactions of the operator. Moreover, the operator is unburdened from operation of UAV sub-systems, although he might have the possibility to access them.

In this configuration, the semi-autonomous systems are acting independently from each other (see Figure 7). Thus, the operator has to care for appropriate allocation of tasks to UAVs as well as re-allocation in case of relevant changes in the situation and supervision of task execution by the supporting ACUs.

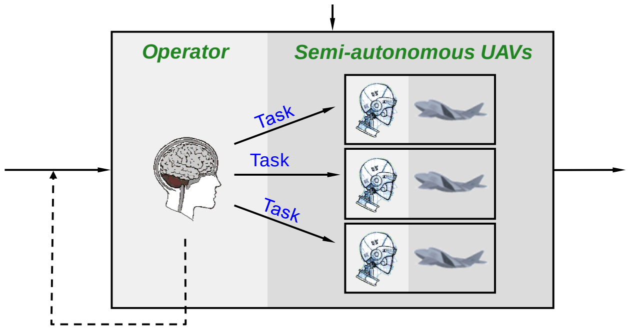

Figure 7: Independent supporting ACUs within UAV guidance work system

The next step combines the semi-autonomous system to one dislocated semi-autonomous system consisting of a team of supporting ACUs. Hereby, each supporting ACU is associated with one UAV and located onboard this UAV (cf. Figure 8).

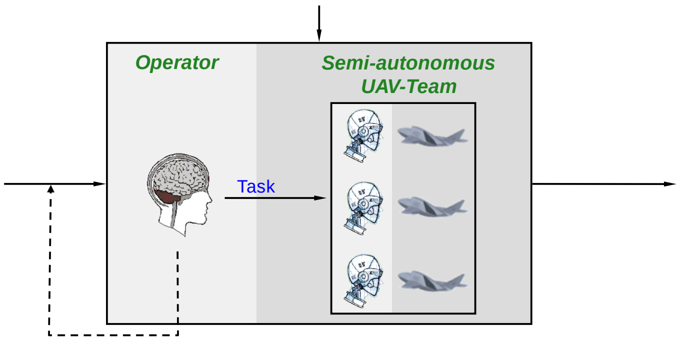

Figure 8: Team of supporting ACUs

This configuration facilitates the allocation of one task to a team of UAVs, that determines necessary sub-tasks as well as an appropriate task allocation by itself. Usually, the team will account for situation changes and adapt if required. While so far the structure of the work system changed in case a UAV was lost or the number of UAVs increased, the operator now has a operation-supporting means at hand, which is much more complex than a semi-autonomous system consisting of one UAV, but which unburdens him from various tasks and tries to maintain situation awareness with respect to the collaboration of UAVs.

Such a semi-autonomous UAV team is capable of executing a given task usually independent from human intervention, but cannot contribute to the work objective of the overall work system as it is not known within the team. In case such a capability is required, the ACUs have to take the shape of operating ACUs (see Figure 9). This step changes the interaction of human operator and ACUs fundamentally as the ACUs are no longer supervised by the human in a hierarchical manner but now form a team within the operating

force which cooperatively tries to achieve the work objective. Thus, the operating ACUs in this setup have to be capable of human-machine cooperation.

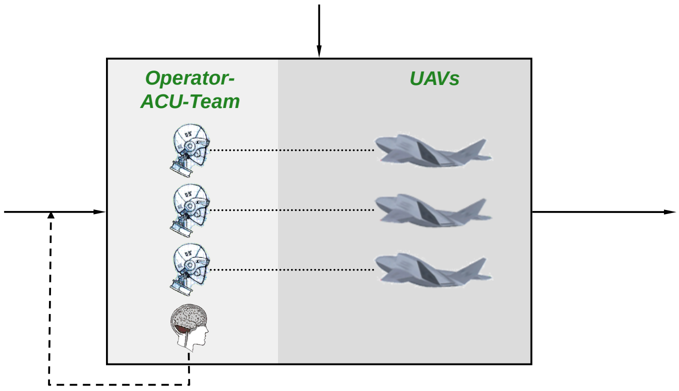

Figure 9: Team of operating ACUs and human operator

Like previously, also this configuration comprises several ACUs because still each ACU is associated with one UAV and located onboard in order to be able to compensate for temporary data link loss and be robust with respect to the loss of a single UAV. Here, a special characteristic of the operating force is used, namely that its elements may be dislocated [4]. Moreover, from the perspective of a work system designer, this set-up follows the recommendation to introduce as much automation as possible into the operating force [4] as it is assumed that the quality of decisions and the performance of the work system as a whole is the better the more automation knows, understands and pursues the work objective.

The difference between a team of supporting ACUs and a team of operating ACUs each of them guiding a dedicated UAV shall be clarified using an example from the MUM-T domain. Here, a manned helicopter has several UAVs guided by the aforementioned ACUs at its disposal for route reconnaissance. This manned helicopter in on the way to a certain site and needs information concerning the planned route. Moreover, there are several alternative routes briefed. In case the UAVs are guided by a team of supporting ACUs, the operator can task them to reconnoitre a certain route, but has to care for re-tasking in case other routes shall be explored because the ACUs do not know that the manned helicopter is on the way to a certain location. In contrast, if the UAVs are guided by a team of operating ACUs, the latter do know the work objective and can hence propose or execute the exploration of alternative routes by themselves in case of situation changes.

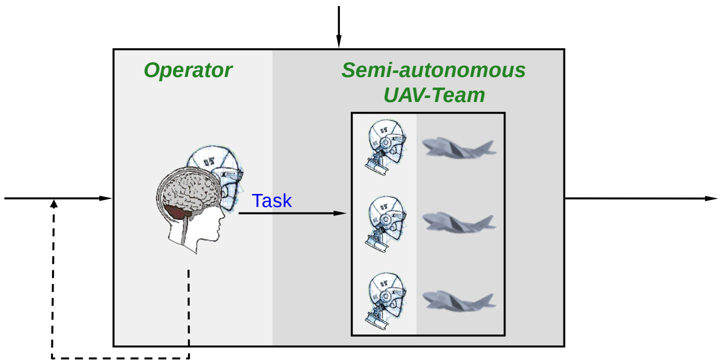

Figure 10: Team of supporting ACUs and operating ACU as operator assistant system

In order to further optimise the UAV guidance work system that has been considered so far, an (additional) operating ACU should be introduced into each configuration [4]. This is especially necessary for set-ups which do not contain an operating ACU yet in order to counteract problems which can be expected with increasing complexity of automation [5]. The new operating ACU behaves as an assistant to the human operator, i.e. it supports him in the execution of his specific tasks. Concerning the supervision of a team of supporting ACUs (cf. Figure 10), such an assistant system would need concepts of team work and appropriate task distribution among the team members in order to be able to derive the need for action. Moreover, knowledge about various alternatives to intervene is necessary as well as an understanding of the operator's current workload and attention focus in order to provide situation adapted support.

3.0 BUILDING ARTIFICIAL COGNITIVE UNITS

As mentioned above, we introduce so-called Artificial Cognitive Units (ACUs) aboard UAVs which are capable of goal-directed planning of their behaviour while considering the current situation. In order to perform well in as many situational configurations as possible these ACUs have to be able to exhibit behaviour on all levels of human performance as introduced by [10]:

- *Skill-based behaviour* is characterised by highly automated and efficient execution of sensori-motor patterns without the need to be aware of. Just like an experienced helicopter pilot can perform a hovering task on this level, a controller stabilising an airborne platform would exhibit the equivalent of skill-based behaviour.
- *Rule-based behaviour* in contrast requires attentional resources from humans and can be observed in standard task situations. Then, a direct situation-task-mapping takes place and the appropriate tasks can be executed by means of skill-based capabilities. Typical rule-based behaviour in the aviation domain can be observed when processing check lists e.g. before departure.
- *Knowledge-based behaviour* is of importance in situations, which have not been experienced before and for which it is not known what should be done next. For example, a pilot might not immediately have an appropriate solution to a situation in which certain mission relevant tasks have to be completed but at the same time unexpected events such as a change of the tactical situation or onboard available resources occur. In order to determine the next steps, at first, the situation has to be understood, then, currently relevant goals will be determined and finally, appropriate actions have to be planned which are suited to achieve the desired state.

While skill-based and rule-based behaviour can be implemented into technical systems quite straightforward, performance on the knowledge-based level is much harder to realise, because developers have to enable the system to understand the situation, to reason about super ordinate goals, to decide what to achieve next and to plan appropriate action sequences.

A paradigm for the design for artificial cognitive systems with such capabilities is the Cognitive Process (CP) [4][11][12], which is depicted in Figure 11. It is a model of human information processing and describes a-priori knowledge models necessary for the implementation of especially knowledge-based behaviour as well as transformation steps actually processing the knowledge.

The transformer *interpretation* uses *environment models* to gather an understanding of the current situation on the basis of *input data* from the environment. This *belief* is the most important input for the *determination of* currently relevant *goals* to be achieved next. These are derived from *desires*, which describe all goals that can potentially be prosecuted by the ACU. The transformer *planning* assembles available *action alternatives* to a *plan*, which is suited to achieve the goals. Finally, the plan is being executed and *instructions* are sent to the output interface.

For the realisation of ACUs based on this paradigm, the cognitive system architecture COSA [11] has been developed which provides a framework implementing application-independent parts of the CP, i.e. knowledge processing by the transformers. Moreover, the development of application-specific a-priori knowledge is supported by the Cognitive Programming Language CPL, which allows to actually formulate environment models, desires, action alternatives and instruction models. [13]

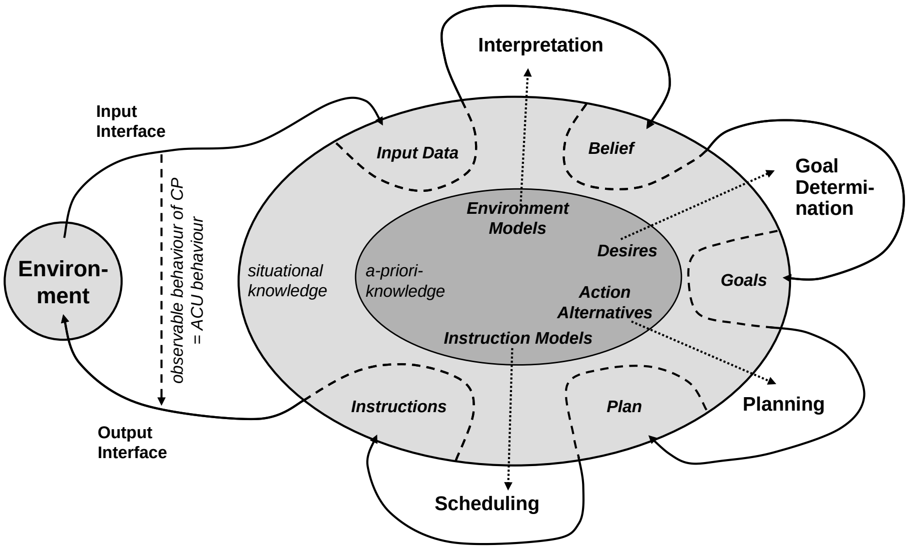

Figure 11: The Cognitive Process for generating knowledge-based behaviour in an ACU

4.0 APPLICATION OF COGNITIVE AND COOPERATIVE AUTOMATION

At the Universität der Bundeswehr (UBM) in Munich, Artificial Cognitive Units have been and are being developed in flight guidance both as assistant systems and onboard mission management systems. Within the last years, focus shifted from manned flight and pilot assistance to UAV guidance. Topics in this area have been single UAV mission management in a reconnaissance mission, predominantly to prove that the Cognitive Process and COSA [11] are a valid approach to UAV guidance as well as cooperative mission accomplishment by multiple UAVs in a hostile area with air-to-ground-attack as primary mission task.

The project described here was focused on the activity of a team of UAVs which is supposed to accomplish a given mission together [14][15]. Each of the UAVs is thereby piloted by an ACU, which is the same for each UAV. In the first place, the ACUs were to behave on the knowledge-based level of performance, i.e. to process situational cues, determine goals, and plan their task agenda. Thus, the design of the a-priori knowledge was deliberately done without knowledge about task situations on the rule-based behavioural level. As a consequence, all UAV actions can directly be tracked back to goals as being determined on the knowledge-based level. From a capability point of view, the focus of the project was cooperative mission management rather than ordinary flight planning. The latter and the coverage of skill-based action control were assumed to be given as well-established conventional automation like autopilot and flight management systems.

4.1 Scenario

The scenario that has been considered consists of a high value hostile target at a certain location which has to be attacked and some threats which have to be avoided or suppressed in order to create a safe corridor to the target (see Figure 12). Some of the threat areas are known before the mission starts while others

may pop up unexpectedly during the course of the mission. One of the UAV team members ("Attack-UAV") is equipped with the means to attack the target. However, this UAV cannot protect itself against threats and has no sensors to detect new threats in the theatre. The SEAD-UAVs in contrast cannot attack the target, but have HARMs with them in order to suppress or destroy SAM-sites and have got sensor equipment for on-board detection of threats as well as approaching missiles. While the UAVs are equipped differently, they are piloted by an ACU of same cognitive capabilities as was earlier alluded to.

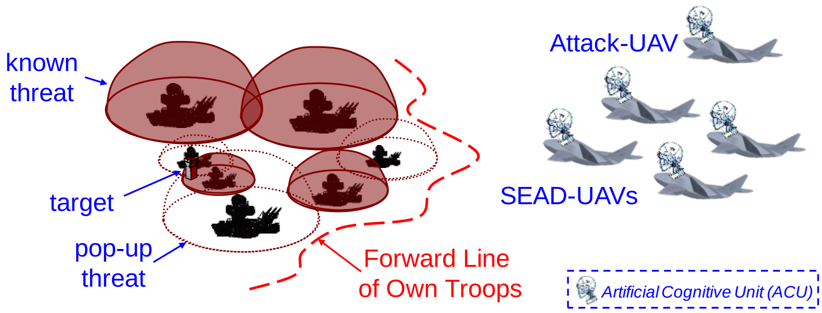

Figure 12: Scenario of SEAD / Attack mission

In order to accomplish the sketched mission, the participating UAVs have to cover the following capabilities [16]:

- Use of UAV equipment of conventional automation, such as an autopilot, a flight management system and a flight planner minimising threat exposure.
- Safe flight, i.e. ensuring that the UAV can fly within 3D-space without colliding with other UAVs or terrain.
- Accomplishment of mission tasks such as "suppress threat".
- Cooperative mission accomplishment, i.e. the ability to cooperate with other UAVs in order to achieve the common objective, namely the mission assigned to the team.

All of these aspects had to be considered when implementing a prototype of the ACUs. Since the focus of the project was on cooperative behaviour, the first three aspects were only covered as much as needed by the cooperative capability. In the following, the chosen work system setup and the development of the prototype with respect to the last aspect, i.e. cooperation, will be described in some more detail.

4.2 Selected Work System Set-Up

The team of UAVs as described above has been designed to be the main operation-supporting means of a work system as depicted in Figure 8. Hereby, a human operator forming the operating force has a semi-autonomous system consisting of the UAV team at hand in order to achieve his work objective. As the ACUs are capable of working together, the operating force can task the team as a whole and receives feedback on task accomplishment by one dedicated spokesman of the team. This spokesman has no decision authority higher than the one of the other team members, but is responsible for communication with the operator.

4.3 Design

The design of the Artificial Cognitive Units is based on the Cognitive Process as presented in chapter 3. This section will detail some of the knowledge models related to cooperative behaviour. At first desires will be specified, followed by action alternatives, instruction models, and finally environment models.

The main ***desires*** for producing cooperative behaviour of ACUs are shown in Figure 13. The first group of desires refers to the achievement of the common objective, i.e. usually the given mission. Therefore, commitments have to be managed and the associated tasks accomplished. Commitment management hereby refers to both accepting and dropping commitments under certain circumstances. Usually, a commitment is accepted by an individual team member or a team if somebody (e.g. operator) requests the accomplishment of a certain task and the accomplishment of this task is judged as being feasible. A commitment should be dropped if it is achieved, irrelevant or unachievable [17][18]. As this does not only refer to own commitments, but also to commitments which other team members have accepted due to own requests, irrelevant dialogs should not be continued. Moreover, a team member should not only consider each commitment separately but should also consider whether all its commitments are achievable as a whole. Team members as individuals are responsible for the actual accomplishment of tasks associated with commitments, therefore, commitments have to be arranged in a certain order in which they shall be considered (so-called ‘agenda’) and actually be complied with at a certain point in time.

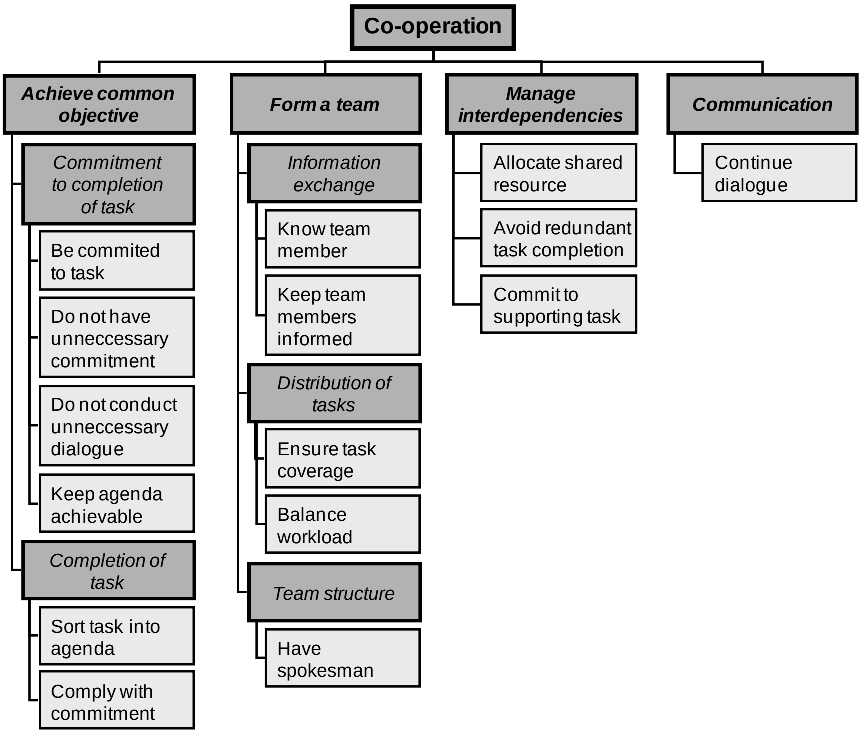

Figure 13: Desires for cooperation (see [19])

Following the requirements derived by [5] to be imposed upon cooperative agents, cooperative behaviour includes appropriate information exchange within the team driven by the desire to have all necessary information about the other team members and to keep them informed with respect to e.g. capabilities, resources, and commitments. The distribution of tasks within a team should be organised in a way that all tasks which should be carried out are assigned to a team member and at the same time workload is balanced among the team members. Finally, in the project described here, the team is structured such that all team members are peers, but that communication with actors not belonging to the team is performed by a spokesman. Therefore, a desire “have spokesman” has been formulated.

Within the scenario described earlier three kinds of interdependencies between team members are relevant. First of all, shared resources (here a corridor which has to be used by all UAVs to fly to the area of interest) have to be assigned to individual team members. Secondly, redundant task assignment shall be

avoided in order to maximise team effectiveness. Thirdly, team members shall support fellow team members by carrying out tasks that facilitate the task accomplishment of the fellow team members. The management of these interdependencies is triggered by appropriate desires.

Communication among the ACUs is structured according to the specific dialogue representation. In order to keep dialogues running, the desire ‘continue dialogue’ becomes active, if the current state of a dialogue requires an ACU to send a message next.

Within this context, various ***environment models*** are required. First of all, a representation of actors is needed, which is instantiated for each actor in the setup, here for each ACU piloting a UAV and for the human operator. Closely related to these models are the ones which describe the various characteristics about capabilities and resources of the actors. Since the actors are organised in a team, also a model is necessary about how a team is to be defined. This model is for example attributed with the members of the team pointing at instantiations of actors. With respect to the common objective of a team, commitments have to be represented. These are further described by the task which is related to the commitment and the actor or team, which is responsible for the commitment. As commitments refer to tasks, tasks have to be modelled. Furthermore, a representation of dialogues, their states and transitions are needed, which again are related to actors and/or teams involved in an interaction.

4.4 Evaluation

The functionality of the system was successfully tested in a simulation. A great number of test runs were conducted. Hereby, different scenarios were used, some of which considering only parts of the overall setup and therefore demanding for particular key capabilities of the ACUs, while others comprised the complete mission scenario in order to test the overall capabilities of the ACUs.

Figure 14 shows the course of a simulation test run with a reduced scenario considering mission accomplishment in a heterogeneous UAV team. It consisted of a team of 2 UAVs, one attack UAV (ID 4) and another one (ID 0) which is able to suppress any of the threats being around. One threat area covers the location of the high value target to be attacked as shown in Figure 14 for the time 00:00.

In the following, both UAVs comply with their commitments, i.e. the attack UAV flies towards the target, while the other UAV (ID 0) starts flying towards the threat (Figure 14, 02:07). After the UAV (ID 0) has successfully suppressed the threat (Figure 14, 03:53), it informs the ACU guiding UAV 4 and the attack UAV adjusts its flight plan and continues its way to the target, now being escorted by the other UAV (Figure 14, 04:31). After having successfully attacked the target, the team continues the request dialogue initiated by the operator and informs him about the successful outcome of the mission. Finally, both UAVs start returning to the home base (Figure 14, 06:29 & 11:49).

Within the project described here, scenarios consisting of up to 10 known and unknown threats and 5 UAVs as well as a corridor for penetrating into the action theatre have successfully been tested in a simulated environment with the ACU prototype used for UAV guidance as described.

Besides the functionality as such also the capability of the prototype to behave on the knowledge-based level of performance was successfully evaluated (see [13]).

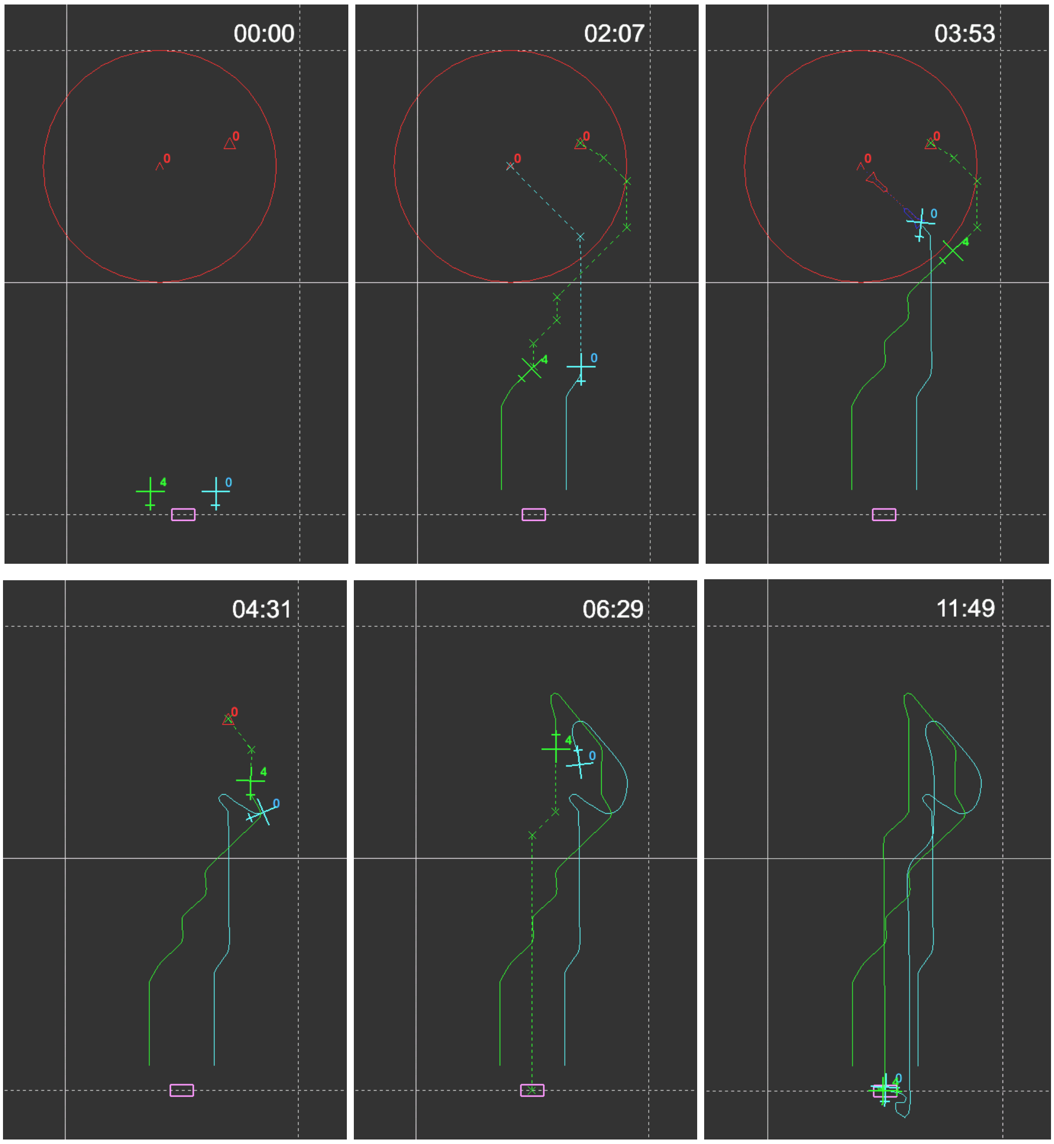

Figure 14: Example of mission accomplishment of a team of 2 UAVs in a test run

4.5 Human-ACU Teaming

Finally, this work also provides the basis for human-machine cooperation although its main focus is on machine-machine cooperation aspects. This add-on could be achieved because of a consequent provision of models of goals for cooperation, of coordination techniques, and of dialogue management related knowledge. Within this context, an experiment was conducted in order to gain first insight to problems arising in human-ACU cooperation and to derive requirements for future ACU development. There, human pilots had to control up to three UAVs equipped with ACUs to accomplish a mission as described at the beginning of this chapter (see [13][20]).

For the experiments the general hypothesis was stated that a human working together with supporting ACUs aboard UAVs is able to handle the situation at large, but is additionally in need of assisting functions. Considering the fact, that the ACUs had been developed as cooperative Supporting ACUs, the work system setup shown in Figure 15 had been chosen for the experiments.

Here, a pilot of a manned aircraft forms a separate work system and gets the same task in the shape of a mission order as the UAV team. Although not being part of the same work system, the pilot and the ACUs form a team due to the fact, that they pursue the same common objective, i.e. the mission. Within the achievement of this common objective, the coordination of their activities can take place by the exchange of messages.

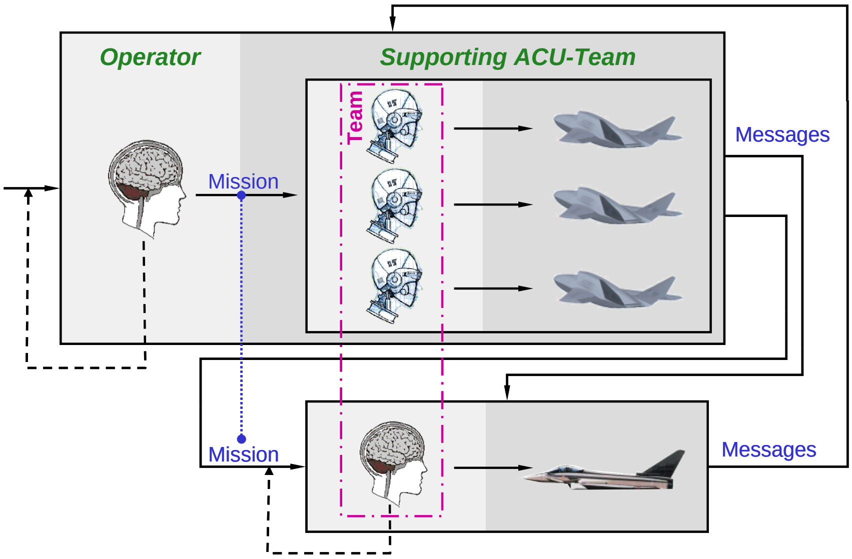

Figure 15: Experimental work system setup

In concrete terms, the mission objective was to destroy a designated target, which was protected by several known and unknown SAM sites. The mission tasks derived from the objective were to attack the target and to suppress or destruct enemy air defence. Two kinds of vehicles were involved, namely one attack aircraft being capable of destroying the target and one or three SEAD aircraft being capable of suppressing or destroying SAM sites. Hereby, several configurations were considered:

- one manned attack aircraft and one SEAD UAV,
- one manned attack aircraft and three SEAD UAVs,
- one attack UAV and one manned SEAD aircraft,
- one attack UAV and one manned and two unmanned SEAD aircraft.

The subjects had a “teaming GUI” (see Figure 16) at their disposal to communicate with the ACUs, where they could generate new mission tasks such as “suppress SAM-site number 5”, assign these to either a team of UAVs or a single UAV and adjust or abort them. Moreover, information about e.g. commitments of team members was provided there.

Additionally, a “navigation GUI” showed the tactical situation, so that the subjects could monitor the scenario and work on mission tasks. It also provided necessary information to the subjects concerning their role as pilot of the manned aircraft. It could be controlled by autopilot commands (here: speed and heading demands) using a keyboard.

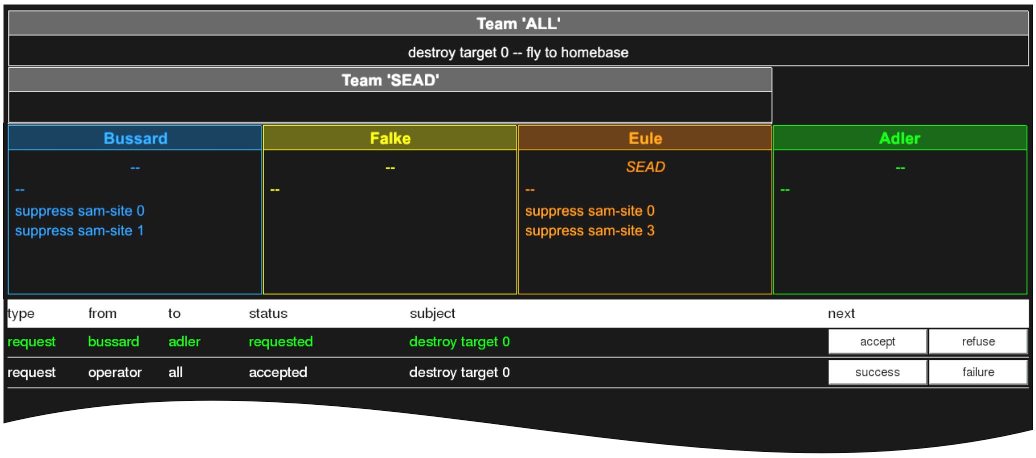

Figure 16: Teaming GUI used in the experiment

Five experienced military air crew members in the age from 31 to 50 served as subjects. These subjects conducted several missions in different scenarios for each of the configurations listed above. Their workload profile was evaluated after each mission using the NASA-TLX method [21]. Moreover, they were interviewed to be able to state problems and suggest system improvements.

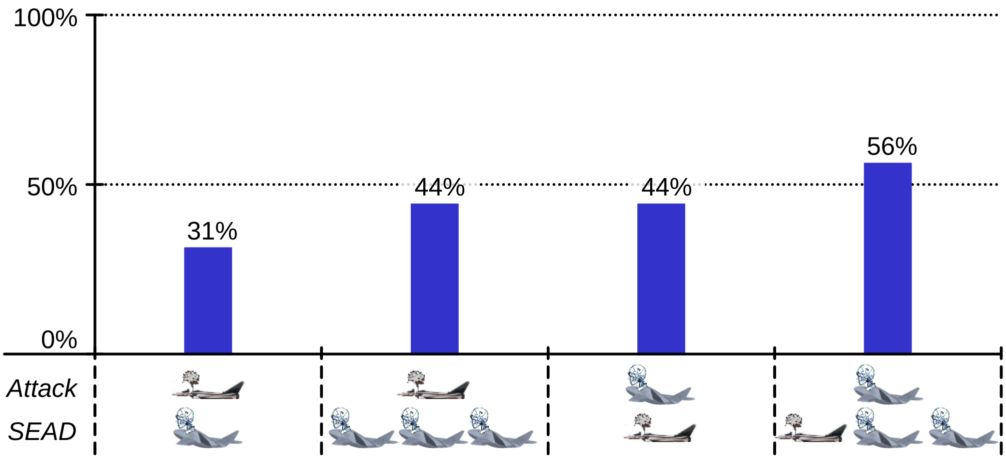

Figure 17: Average workload of subjects in different configurations

The performance of the human-machine team was very good. More than 90% of all missions could be completed successfully. Regarding the workload of the subjects, it was on a medium level in all configurations that have been investigated (see Figure 17 for the average workload of humans in different configurations). Interestingly, there is only a small increase in workload when changing the number of UAVs within the team from one to three. Moreover, the increase in workload when changing the human role from attack to SEAD is as large as when adding two UAVs, which could be related to different performance of UAVs in the SEAD and attack role.

These results show that in principle human-ACU cooperation is possible with the approach of cognitive and cooperative automation and that workload is on a medium level even though ACUs were not designed to work together with humans. Still, further improvement potential was identified in the following areas after having analysed interview protocols:

- *Team Structure.* The introduction of a hierarchical team structure is encouraged, although team members shall be capable of situation dependent deviation from leader input.
- *Abstraction of Interaction.* Interaction with ACUs shall be as abstract as possible (e.g. specification of tasks for UAV team rather than detailed instructions for single UAVs). In particular it shall be possible to give instructions on different abstraction levels.
- *Level of Automation.* ACUs shall be able to act on a high level of automation but the actual level shall be adaptable or self-adapted to the current situation and task.
- *Teamwork.* Cooperation of humans and ACUs shall be based on a common agenda and anticipate future actions of team members.
- *Task completion.* The capability of ACUs to actually accomplish tasks has to be improved.
- *Communication within team.* Vocabulary shall be adapted for more intuitive understanding of humans. Moreover, the number of dialogs and messages shall be reduced to a minimum in order to avoid overload of humans.
- *Assistant System.* The human team member shall be supported by an electronic assistant providing him or her with situation awareness concerning team members, task assignment and information flow within team as well as accomplishment of his or her primary mission related task, i.e. aircraft guidance.

Ongoing work is intended to account for these findings and bring together the different aspects of human-machine and machine-machine cognitive cooperation in manned-unmanned multi-agent scenarios. In the field of supervisory control of UAVs the question of how to reduce the operator-to-vehicle ratio will be predominant. Hereby, cognitive and cooperative automation offer solutions for many of the upcoming questions.

5.0 CONCLUSIONS

Our research work on cognitive and cooperative automation in military aerial applications is driven by the goal to enable a pilot or UAV operator to eventually guide more than one aircraft at the same time. Undoubtedly, the workload in suchlike work situations can easily exceed certain unwanted limits especially when anticipating a dense and dynamic wartime theatre. However, current military scenarios require the close cooperation between manned and unmanned assets. This entails even airborne UAV guidance and an increasing vehicle to operator ratio. Nevertheless, from a pilot’s perspective it is undisputable that operating multiple aircraft with today available guidance and control technologies would be simply not worth any discussion. The guidance concept based on the approach of cognitive and cooperative automation includes functional aspects like

- the availability of control strategies using **higher level tasks assignments** instead the usage of parameters for action control,
- the assumption of **goal oriented rational behaviours** following these tasks including the capability of a reasonable **self-assignment of tasks** and the making of local decisions in case of disrupted communication or situational circumstances beyond the perception of the operator, and

- the existence of a **cooperative work relationship** directed towards common objectives between the operator and the controlled aircraft and even between the unmanned aircraft if needed.

Involving artificial cognition into the work system design based on a better insight on human cognition mechanisms, as we are utilising in our approach, leads to further opportunities with respect to human-machine system performance enhancements. The required functions of artificial components supporting the human operator, in particular artificial cognition, can be specified on a more rational basis, because it is better known where the human operator really needs support. Effective cooperation on a cognitive level between artificial systems (automation) and the human operator can be made a design characteristic. This can be achieved by use of quantitative models of human behaviour like those we have in mind ourselves when we are cooperating in a team e.g. models of operator workload in certain work situations or models concerning available human resources. The use of the knowledge about the capabilities and the architecture of human cognition as a reference is an eligible way to achieve better architectures for artificial cognitive systems.

In fact, it is not an easy task to implement a system involving artificial cognition as claimed by our paper. However, there are already several field implementations on their way. But non of these, though, has yet reached that high level of flexibility, interoperability, and autonomy accompanied with a maximum performance in a sense of human factors and human-automation integration characteristics that military user and operators require and deserve. We hope to be substantially contributing to the achievement of this goal by our interdisciplinary and embracing approach, being aware that many unsolved problems still have to be tackled.

As to our belief, one of the most relevant fields of future research will be associated with the term of *adaptive autonomy*. Our experimental findings clearly indicate that there is a strong need for self adaptation of the level of autonomy of the UAVs. Operators will demand to interact with the UAVs on various abstraction levels ranging from dedicated parameter settings over task based guidance to team capability management. Given that, combined with appropriate interfaces (e.g. speech) will open the door to human-automation cooperation akin to cooperation in purely human teams.

REFERENCES

[1] Thomas B. Sheridan (1992). Telerobotics, Automation, and Human Supervisory Control. Cambridge, MA: MIT Press.

[2] Reiner Onken (2002). Cognitive Co-operation for the Sake of the Human-Machine Team Effectiveness. In: NATO RTO-Meeting Procedures MP-088, HFM-084: The Role of Humans in Intelligent and Automated Systems. Warsaw, Poland, 2002.

[3] Claudia Meitinger & Axel Schulte (2006). Cognitive Machine Co-operation as Basis for Guidance of Multiple UAVs. In: NATO RTO-Meeting Proceedings HFM-135: Human Factors of Uninhabited Military Vehicles as Force Multipliers. Biarritz, France, 9th-11th October 2006.

[4] Reiner Onken & Axel Schulte (2009). System-ergonomic Design of Cognitive Automation in Work Systems – Dual-Mode Cognitive Design of Vehicle Guidance and Control Work Systems. Studies in Computational Intelligence, Vol. 235. Heidelberg: Springer.

[5] Charles E. Billings (1997). Aviation Automation – the Search for a Human-Centered Approach. Mahwah, NJ: Erlbaum.

[6] Lisanne Bainbridge (1983). Ironies of automation. Automatica, 19(8), 775-779.

[7] Reiner Onken (1994). Basic Requirements Concerning Man-Machine Interactions in Combat Aircraft. In: Proceedings of the Workshop on Human Factors / Future Combat Aircraft. 1994.

[8] Mark W. Scerbo (2001). Adaptive automation. In: W. Karwoski (Ed.). International Encyclopedia of Ergonomics and Human Factors. (pp. 1077–1079). London: Taylor & Francis.

[9] Diana Donath & Axel Schulte (2009). Behaviour Model Based Recognition of Critical Pilot Workload as Trigger for Cognitive Operator Assistance. In: 8th Conference on Engineering Psychology & Cognitive Ergonomics, in conjunction with HCI International. San Diego, CA, 19th-24th July 2009.

[10] Jens Rasmussen (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and other Distinctions in Human Performance Models. IEEE Transactions SMC. 13(3).

[11] Henrik Putzer & Reiner Onken (2003). COSA – a generic cognitive system architecture based on a cognitive model of human behaviour. International Journal on Cognition Technology and Work. 5, 140-151.

[12] Axel Schulte, Claudia Meitinger & Reiner Onken (2009). Human Factors in the Guidance of Unmanned Vehicles: Oxymoron or Tautology? The Potential of Cognitive and Cooperative Automation. In: International Journal on Cognition Technology and Work. 11, 71-86.

[13] Claudia Meitinger & Axel Schulte (2009). Human-UAV Co-operation Based on Artificial Cognition. In: 8th Conference on Engineering Psychology & Cognitive Ergonomics, in conjunction with HCI International. San Diego, CA, 19th-24th July 2009.

[14] Claudia Meitinger & Axel Schulte (2006). Human-centred automation for UAV guidance: Oxymoron or tautology? – The potential of cognitive and co-operative systems. In: *Proceedings of the 1st Moving Autonomy Forward Conference*. Lincoln, UK, 21st-22nd June 2006.

[15] Axel Schulte & Claudia Meitinger (in prep.). Introducing cognitive and co-operative automation into UAV guidance work systems. In: Michael Barnes & Florian Jentsch (Eds.) *Human Robot Interactions in Future Military Operations.*

[16] Jon Platts, Petter Ögren, Patrick Fabiani, Vittorio di Vito & Rüdiger Schmidt (2007). *Final Report of GARTEUR FM AG14*. GARTEUR/TP-157.

[17] Philip R. Cohen & Hector J. Levesque (1990). Intention is choice with commitment. *Artificial Intelligence, 42, 213-261.*

[18] Nicholas R. Jennings (1994). *Cooperation in Industrial Multi-Agent Systems*. Singapore: World Scientific.

[19] Axel Schulte & Claudia Meitinger. Cognitive and Cooperative Automation for Manned-unmanned Teaming Missions. In: NATO RTO Lecture Series SCI-208 on *Advanced Automation Issues for Supervisory Control in Manned-unmanned Teaming Missions.* Monterey, USA; Torino, Italy; Amsterdam, Netherlands. September 2009.

[20] Andreas Rauschert, Claudia Meitinger & Axel Schulte (2008). Experimentally Discovered Operator Assistance Needs in the Guidance of Cognitive and Cooperative UAVs. In: *Proceedings of the*

Conference of Humans Operating Unmanned Systems (HUMOUS'08). Brest, France, 3rd-4th September 2008.

[21] Sandra G. Hart & Lowell E. Staveland (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In: P. A. Hancock & N. Meshkati (Eds.) *Human Mental Workload*. Amsterdam: North Holland Press, pp. 139-184.